



Analysis of a Hovering Rotor in Icing Conditions

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Abstract

A high fidelity analysis method is proposed to evaluate the ice accumulation and the ensuing rotor performance degradation for a helicopter flying through an icing cloud. The process uses computational fluid dynamics (CFD) coupled to a rotorcraft comprehensive code to establish the aerodynamic environment of a trimmed rotor prior to icing. Based on local aerodynamic conditions along the rotor span and accounting for the azimuthal variation, an ice accumulation analysis using NASA's Lewice3D code is made to establish the ice geometry. Degraded rotor performance is quantified by repeating the high fidelity rotor analysis with updates which account for ice shape and mass. The process is applied on a full-scale UH-1H helicopter in hover using data recorded during the Helicopter Icing Flight Test Program.

Introduction

Whether a helicopter is used for emergency rescue, military missions, or commercial business there are strong desires to operate them safely in all climate conditions. Operating helicopters in icing conditions is particularly dangerous because rotor blades are especially susceptible to ice growth due to their small chord. Quick accumulating ice on rotor systems leads to increased vibration, rapid loss of lift, and a large power increase to sustain flight. Shed ice from spinning rotors is common and creates hazardous projectiles.

Ice protection systems can guard against adverse effects of ice accumulation. These systems require certification for commercial use and qualification for military applications. Both involve extensive flight tests which are expensive and time consuming. Several icing seasons are usually required to cover the boundaries of the flight envelope. Model-scale and full-scale laboratory tests assist in the certification or qualification, but scaling effects can complicate the interpretation of results.

A highly accurate ice accumulation and rotor performance degradation prediction system can help in understanding rotorcraft behavior and limitations in adverse weather. Analytic results can guide flight test planning and add a layer of safety during icing trials. Furthermore the system can assist in reliably extrapolating model scale testing results to full-

scale flight conditions. This could result in less flight tests for certification or qualification.

The approach taken to develop an icing analysis system for rotors leverages methods developed for fixed-wing aircraft. Bidwell (Ref. 1) coupled ice accretion analysis with computational fluid dynamics (CFD) to evaluate ice on a high-lift wing configuration. He used Lewice3D (Ref. 2) to evaluate droplet trajectories, heat transfer, and ice growth while relying on OVERFLOW (Ref. 3) or CFD++ (Ref. 4) for aerodynamic analysis. OVERFLOW is well suited for aerodynamic assessments of rotorcraft and therefore Bidwell's approach is a natural point of departure for an icing analysis system for rotors.

A high-fidelity ice analysis system for helicopters is the subject of this paper. The paper begins with an overview of the analysis approach and then offers a description of the process to generate an aerodynamic solution for a trimmed rotor in forward flight. The process to predict ice on the rotor blades utilizes information from the rotor flow field and is described next. Analysis of the iced rotor concludes the rotor icing analysis process. The process is described for a helicopter in forward flight but is applied to a hover situation which represents the first step in validating the method. Following the results of the hover analysis are conclusions.

Analysis Approach

The high fidelity icing analysis approach developed for rotor systems follows four basic steps. These are:

- Establish rotor trim and clean rotor performance and the initial flow field environment using CFD or coupled CFD/CSD as appropriate;
- Extract representative 2D airfoil conditions for blade sections at radial and azimuthal locations;
- Predict ice buildup on the rotor accounting for the diverse operating environment of the rotor;
- Reestablish rotor performance for the iced blades.

The approach is appropriate to address ice accumulation on rotors for all flight regimes from hover to high-speed forward flight. The process is shown pictorially in Figure 1.

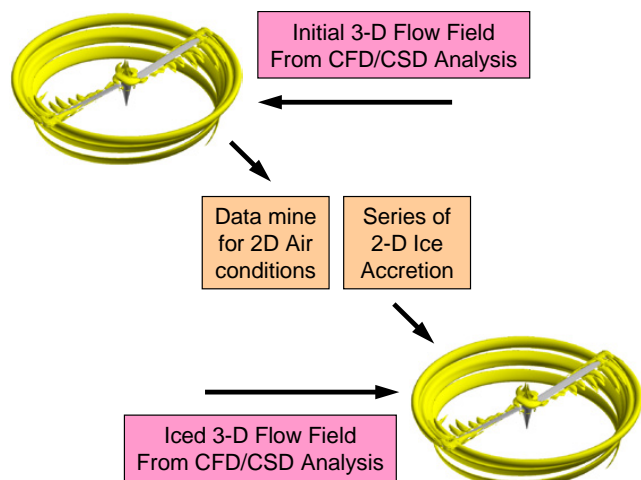


Figure 1.—High-fidelity ice accretion and performance degradation methodology.

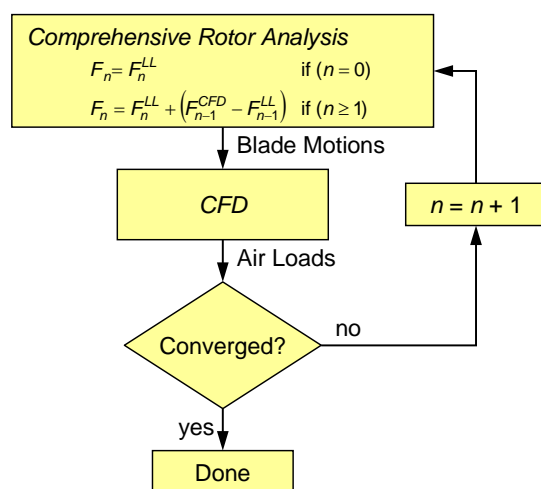


Figure 2.—CFD/CSD coupling process.

The process begins with a CFD or coupled CFD/CSD (computational structural dynamics) analysis of the rotor in flight. In this scenario, atmospheric conditions of the icing event are modeled with the exception of water drops. Rotor performance for clean blades is obtained and serves as the baseline with which to compare iced rotor performance. The numerical solution provides flow details including pressure distributions and air loads that are useful for the ice accretion analysis. Coupling CFD with CSD means that the blade response to air loads (flapping, lead-lag motion, and aeroelastic bending) is represented in the solution and that control settings are trimmed to provide a balanced rotor. It is not always necessary to couple CFD with CSD for stiff rotors and prescribed controls or for rotors in hover. For these cases the analysis can be simplified by using a pure CFD solution.

Generally, rotary-wing aeromechanics is inherently multidisciplinary, where elastic deflections of the rotor blade interact strongly with aerodynamic forces. Aeromechanics predictions require a coupling of structural dynamic and

aerodynamic analysis within an umbrella that solves both simultaneously and also provides a solution for aircraft or rotor trim. The rotorcraft industry has developed comprehensive analyses (Refs. 5 to 7) that apply modeling technologies that are well suited for this. They include non-linear finite elements for structural dynamics analysis, lifting line theory for aerodynamics analysis, and trim algorithms to find rotor controls that balance forces. Finite-element analysis captures relatively large deflections and the tension field induced by rotation; lifting line theory is supplemented with corrections for unsteady aerodynamics including dynamic stall and airfoil section load coefficient lookup tables (so-called C81 format) that are functions of Mach and angle of attack.

Efforts to replace the lifting-line air loads models within comprehensive codes with CFD-based analysis have been ongoing (Refs. 8 and 9). Recent efforts with Navier-Stokes CFD coupled with comprehensive codes have demonstrated improved air loads predictions, particularly where large unsteady aerodynamic forces cause blade deflections that feed back into the aerodynamics. Empirical correction models have not been able to capture all aerodynamic phenomena of importance to blade loads and performance, but CFD has shown promise.

Comprehensive codes compute air loads as needed during the convergence process. Trim magnifies the number of times air loads must be computed, so the long run-time for CFD makes direct substitution of lifting-line impractical. A method of substitution has been developed called loose-coupling. This method allows trim to use lifting-line air loads during trim, while successively using the CFD solution. The method is outlined in Figure 2. At iteration $n = 0$, the comprehensive code trims and converges with only lifting-line air loads as usual. Blade motions for one rotor period are then passed to the CFD solver. These motions contain gross pitching motions from controls as well as the elastic response. It is not necessary to achieve a perfect periodically-converged solution from CFD at this point; successive iterations between the comprehensive code and the CFD code move the solution toward convergence. At iteration $n \geq 1$, CFD-based air loads are passed back into the comprehensive code and used with lifting-line air loads from the previous solution. The comprehensive code continues to compute lifting-line air loads during trim and convergence and while adding the previous iteration CFD and lifting-line “delta” for the total air load to drive the aeromechanical solution. These iterations continue until there is no change in trim controls or air loads, at which point the lifting-line air loads from the previous iteration cancel the lifting-line air loads from the current iteration leaving only the CFD as the total air load. This process is fairly efficient with CFD, and usually requires simulation of between two and five rotor revolutions as trim and periodic convergence move together.

The solution is naturally time dependent, but periodic, as the blades rotate around the azimuth and respond to the air loads. Ice accretion is influenced by the local aerodynamics which changes over the course of a rotor revolution. To harvest the

aerodynamic conditions, the CFD/CSD solution is saved for several blade positions in a rotor revolution providing snapshots of the flow field at several instances in time. Accreting ice using a 2D strip approach is possible provided representative conditions can be data mined from these solutions. Specific required data include local angle of attack and relative velocity as a function of blade radial and azimuthal position. There are several ways to extract this information. Ideally, the extracted conditions should produce a 2D pressure distribution on an airfoil that is identical to the instantaneous pressure distribution from the 3D solution.

Extracted pressure from the rotor solution is typically presented in coefficient form using the hover tip speed as the reference velocity, V_{tip} . Assuming mostly 2D flow along the blade and that the flow stagnates on the blade, the pressure coefficient can be renormalized by V_{2D} such that $C_{p_{max}}$ is equal to $1/\sqrt{1-M_{2D}^2}$. The 2D free stream Mach number that satisfies this requirement is

$$M_{2D} = \sqrt{\frac{1}{2}(\sqrt{A^4 + 4A^2} - A^2)}, \quad (1)$$

where

$$A = M_{tip}^2 C_{p_{max}}. \quad (2)$$

The reference 2D velocity is then $M_{2D} a$ where a is the speed of sound.

A representative angle of attack for the 2D ice accretion strip approach can be determined a number of ways, for example, by utilizing a 2D aerodynamic database of Mach numbers, normal force, and angle of attack or using an airfoil aerodynamic analysis tool to find the angle of attack that best matches the 3D pressure distribution for V_{2D} .

The extracted aerodynamic conditions along with the conditions of the icing environment allow for an ice accretion analysis. The process begins by considering one radial location at a time and segmenting the icing encounter into a number of smaller time steps. At a radial location, ice is accumulated over these small time increments using the 2D conditions which vary as a function of azimuth as illustrated in Figure 3. Each subsequent ice accretion is accumulated on top of the ice growth calculated from the previous time step. At the conclusion of the final time step, the ice accumulated over the length of the blade will represent ice growth influenced by the aerodynamic conditions encountered over all azimuthal positions.

The ice analysis follows a similar approach to Bidwell (Ref. 1) which involves a coupling between Lewice3D and CFD. Here, Lewice3D evaluates drop trajectories, thermodynamic equilibrium, and ice growth for a blade section using an airfoil aerodynamic solution from CFD. For consistency the airfoil aerodynamic solution is also computed

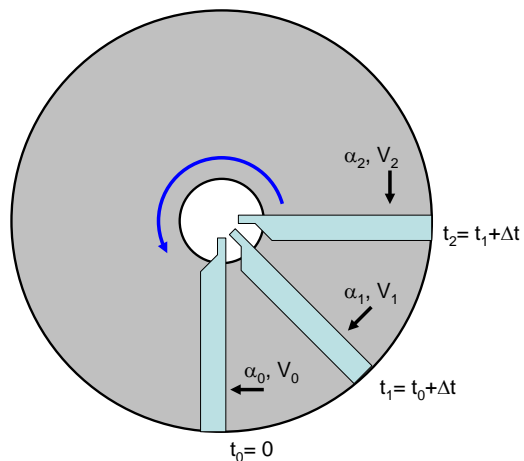


Figure 3.—Ice build-up prediction process.

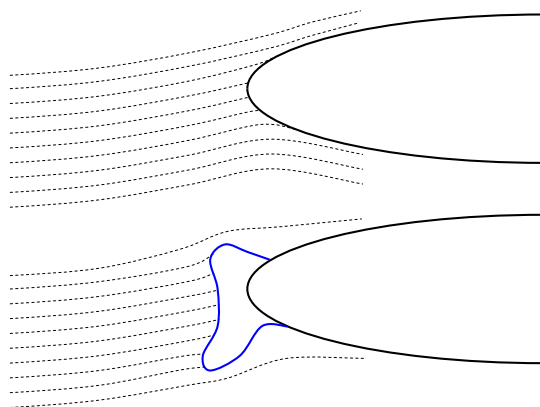


Figure 4.—The influence of accreted ice on drop trajectories.

with OVERFLOW. Depending on the extent and shape of the accreted ice, the ice growth may be computed in a multi-step approach. As the ice grows, blade aerodynamics, droplet trajectories, impingement limits, and collection efficiency can be significantly altered. This is illustrated in Figure 4. It may be necessary to update the airfoil geometry and airfoil aerodynamic solution to reflect intermediate ice growth. Generally for rotors in forward flight, the icing event can be segmented in small enough time increments to perform single-step ice accretion. However, in the case of hover, where there are no azimuthal variations in the 2D aerodynamic conditions, a multi-step ice accretion could improve prediction fidelity.

Once the ice has been established on the blade, the CFD/CSD analysis process is repeated for the iced rotor. The 3D rotor grid is modified to account for the ice shape on the blade. The input to the CSD analysis is modified to reflect the additional mass and change to the blade center of gravity. It is assumed that the effect on blade stiffness is small. Rotor performance degradation is obtained by comparing the forward flight performance characteristics of the iced rotor to

the baseline rotor. One important element of rotor performance degradation is the increase in power for the same thrust. In addition to this metric, the coupled CFD/CSD solutions will give insight to the change in blade loads and control positions for trim.

One important element of ice prediction of rotors is ice shedding. Rotor centripetal force and aerodynamic loads can cause segments of ice to leave the rotor, increasing vibration levels. The prediction of ice shedding events, though important, is not currently addressed in this process.

Hover Test Case

During the winter of 1982-83, the NASA Lewis Research Center and the U.S. Army conducted the Helicopter Icing Flight Test (HIFT) program to study the characteristics of a helicopter in near hover conditions subjected to icing conditions. As a part of this program, an attempt was made to document, as completely as possible, the ice formations on the main rotor blades and the resultant rotor performance degradation for the purpose of validating analytical techniques. These results are taken as reference to validate the simulation approaches presented in this paper. The helicopter used for the HIFT Program was a Bell UH-1H and it was tested at the Canadian National Research Council (NRC) spray rig facility at Uplands Airport, Ottawa, Canada. Figure 5 shows a photograph of the test.

Though it was desired to achieve near hover conditions, the spray rig required a wind speed of a least 6 knots to carry the icing cloud out over the helicopter. Due to the low speed, a hover flight condition is assumed for the analytic predictions. From the five flights tested, summarized in Table 1, condition 'E' was selected to be reproduced with numerical computation due to the low gusts and the existence of the ice on the rotor up to 92 percent of the span. The median volumetric drop diameter for these flight conditions is 30 μm and the total accretion time is 3 min.

TABLE 1.—SUMMARY OF HOVER ICING FLIGHTS TEST CONDITIONS DURING THE HIFT PROGRAM

Flt no.	Wind speed (m/s)	Gusts	LWC (g/m^3)	T_∞ ($^\circ\text{C}$)	Time (min)	Ice extent (r/R)
A	3.6	Medium	0.4	-12.	4.5	0.75
B	5.1	Medium	0.4	-9.5	4.25	0.65
C	3.0	Medium	0.4	-17.	4.0	----
D	2.1	Low	0.4	-21.	6.0	----
E	4.6	Low	0.7	-19.	3.0	0.92

The stereo photography tracing techniques was adopted, among others, to document rotor ice accretion shapes. Ice shape tracings were made for several sections along span-wise locations. An exhaustive description of the test and results of the HIFT Program can be found in References 10 and 11.

The rotor for the Bell UH-1H has a conventional NACA 0012 airfoil with a constant chord of 21 in. The span is



Figure 5.—Photo of the Army UH-1H helicopter hovering in the NRC icing cloud.

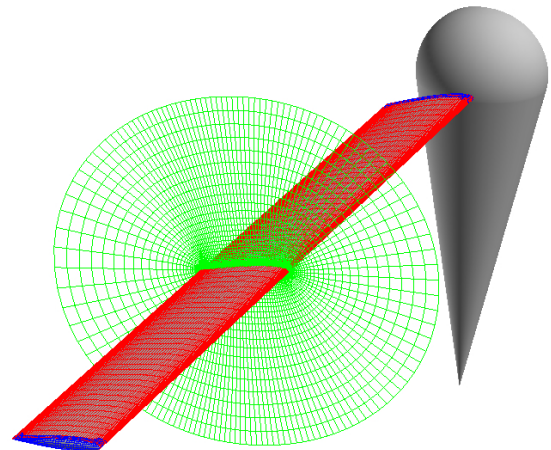


Figure 6.—Isolated rotor grid for the UH-1H; every 4th point shown for clarity.

288 in. and the main rotor area is equal to 1809.5 ft^2 , with a rotational speed ω of 33.9 rad/sec and a resulting Mach number tip of about 0.79. The rotor blade has a linear 10.9° twist along the span. The maximum gross weight of the UH-1H is about 9500 lb. This value is considered for the estimation of the thrust coefficient.

Results

The clean UH-1H hover performance is estimated using an isolated rotor model. A rotational source term is added to the governing equations of motion to obtain a steady state solution in a blade-fixed reference frame using the technique described in Reference 12. The grid system for the clean rotor is shown in Figure 6 and features a C-grid topology in the chord direction with 533 points. Along the span 275 points are used to define the geometry as ice will be predicted in 1-in. increments across the radius. The hover model has a fictitious center body to prevent blade root vortices from

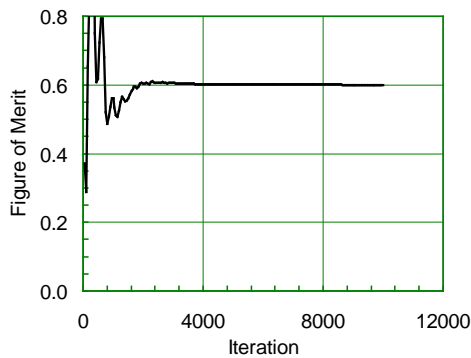


Figure 7.—Figure of merit convergence with OVERFLOW for the UH-1H rotor in hover, collective 7° and flight conditions 'E'.

circulating. The blades are physically disconnected from the center body to easily adjust the blade collective pitch angle.

The solution was computed with OVERFLOW 2.1g using a central differencing scheme for the Euler terms. The Spalart Allmaras turbulence model was used assuming a fully turbulent boundary layer over the blade. The turbulence model was turned off in the off-body wake region as a simplistic engineering approach to maintain blade tip vortex strength which tends to prematurely dissipate in traditional RANS solutions. Typical hover solutions with this grid system require about 10,000 iterations to converge the figure of merit to within 0.002 (Figure 7).

The solution for a rotor thrusting at 9500 lb is data mined for representative 2D airfoil conditions to be used in the strip analysis for ice accumulation. The chordwise pressure distribution is extracted at several radial positions and normalized with a reference velocity according to Equation (1). Local angles of attack are found such that when applied in a 2D airfoil analysis with the reference velocity similar pressure distributions are obtained. The velocity and angle of attack distribution used to accrete ice on the UH-1H rotor is shown in Figure 8. Since this is a hover condition, there is no azimuthal variation.

The ice event time for flight condition E is 3 min which could produce significantly large ice shapes. To address the influence of accreting ice on the final ice shape, the icing analysis was performed in 1 and 3 steps for the airfoil condition at 62 percent R. In the 3-step analysis, ice is grown for 1 min before the geometry and aerodynamic solution is updated. The comparison of the 1-step and 3-step approach is shown in Figure 9. Though some differences exist, the shapes are close enough to believe that both will produce similar rotor performance degradation. Due to the additional computational expense of the 3-step approach, rotor ice across the blade is accreted in 1 step.

The accreted ice shape for the blade is shown in Figure 10. To generate this shape, icing analyses are performed in 1-in. increments from blade root to blade tip. Moderate amounts of ice are grown towards the root end where the Mach number is generally low and the ram temperature is also relatively low.

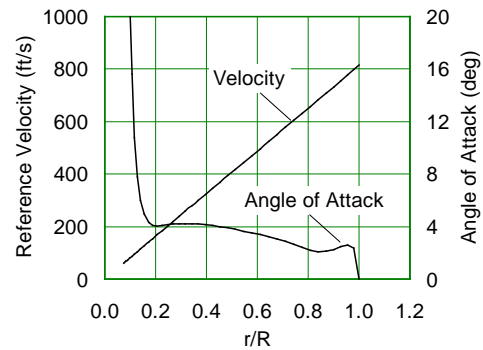


Figure 8.—Representative 2D aerodynamic conditions along the rotor radius.

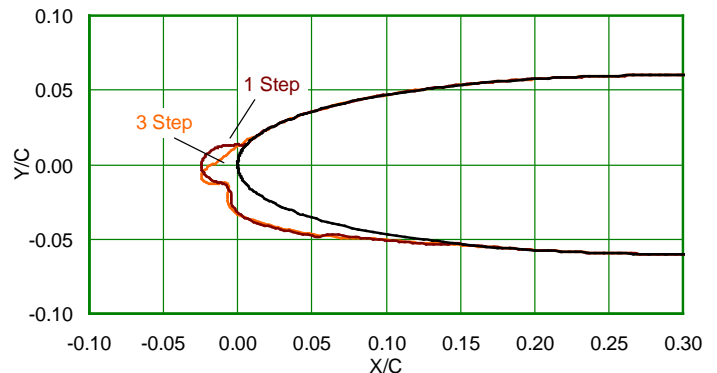


Figure 9.—Ice accreted at 62 percent rotor radius computed in 1 and 3 steps.

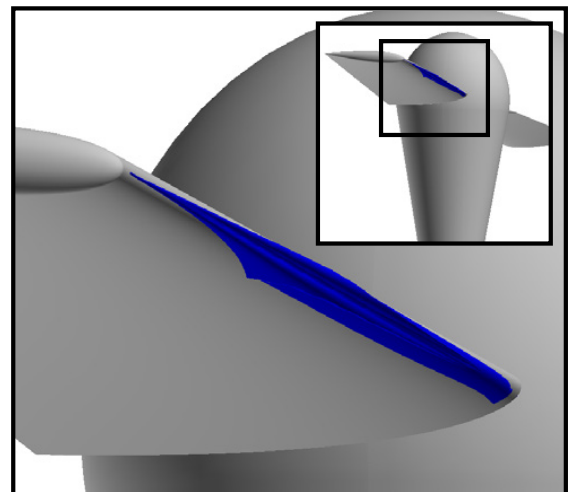


Figure 10.—Predicted ice along the span of the blade; ice analysis is performed in 1-in. increments.

Further outboard, just beyond the mid-radius, the ice shapes are larger in size. Beyond 65 percent, the ice shapes begin to get smaller as the ram temperature increases.

The predicted ice shapes using the 1-step approach correlate well to measured data. Figure 11 shows a sample of the correlation at 4 radial stations: 45, 62, 70, and 79 percent.

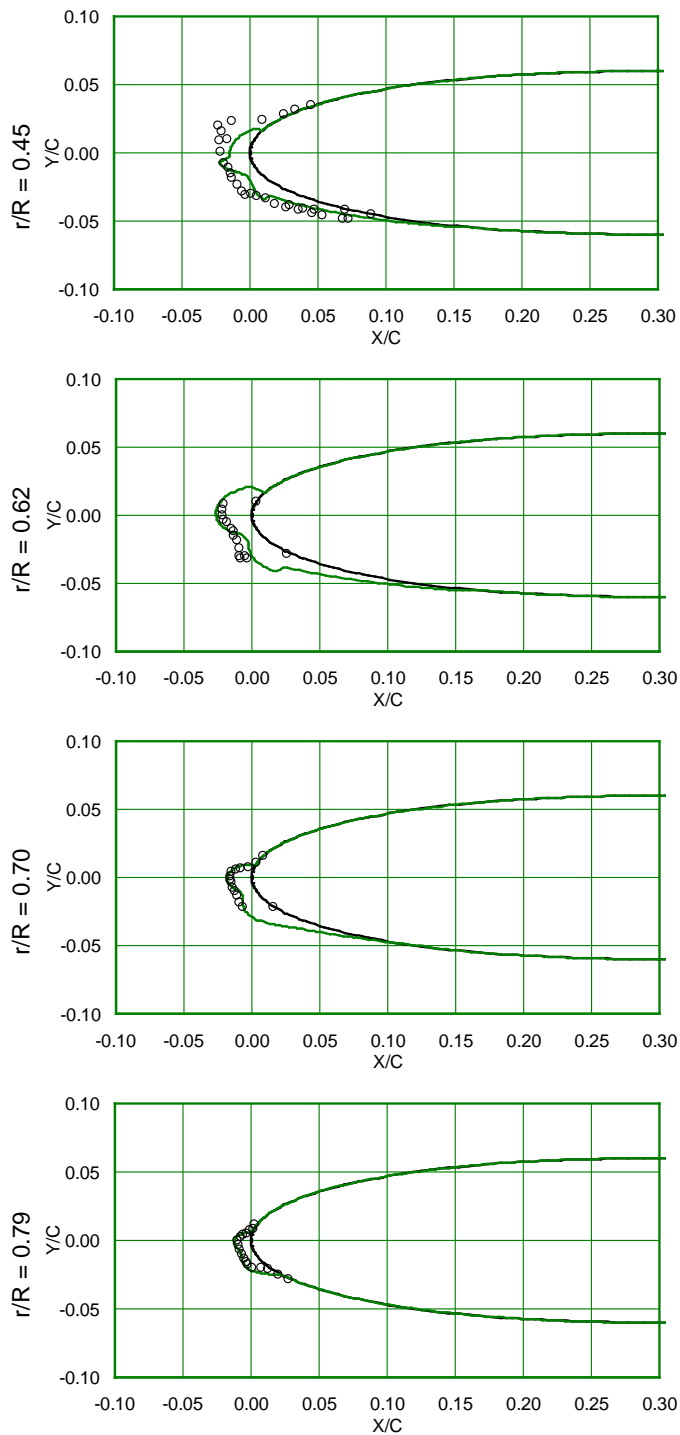


Figure 11.—Comparison of predicted and measured ice shapes for Flight E of the HIFT program.

The iced rotor is analyzed in the same manner as the clean rotor. The grid density is unchanged between the clean and iced rotor because it is sufficient to capture the features of the ice. The predicted rotor power and the power increment needed to maintain hover is shown in Figure 12. The HILT

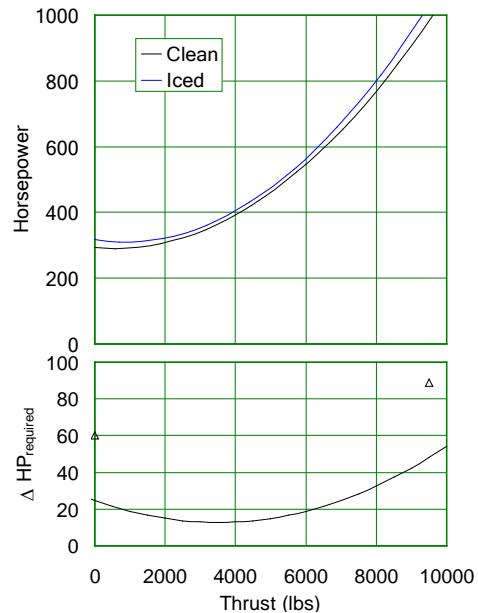


Figure 12.—Predicted and measured rotor performance degradation for Flight E of this HIFT program.

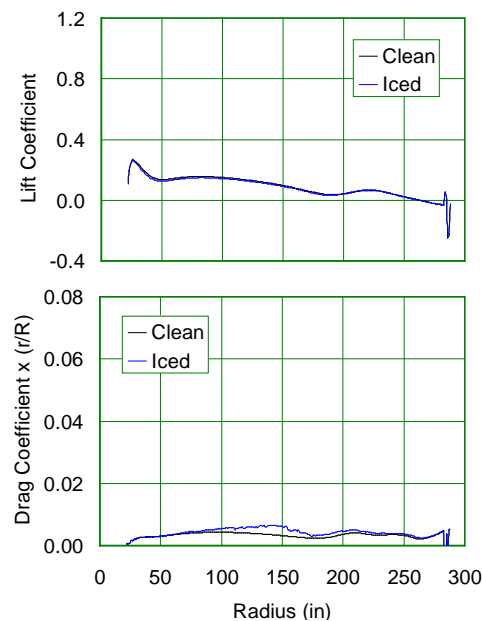


Figure 13.—Blade loads for the clean and iced rotor near zero-thrust.

program measured the increase in power required at two conditions: First, directly after ice accumulation in out-of-ground-effect (OGE) hover, then while on the ground with flat pitch. The two data points are indicated as open symbols in Figure 12. The predicted power increase is roughly 50 percent of the experiment.

The air loads along the blade near the zero-thrust condition (Figure 13) and near the maximum gross weight (Figure 14)

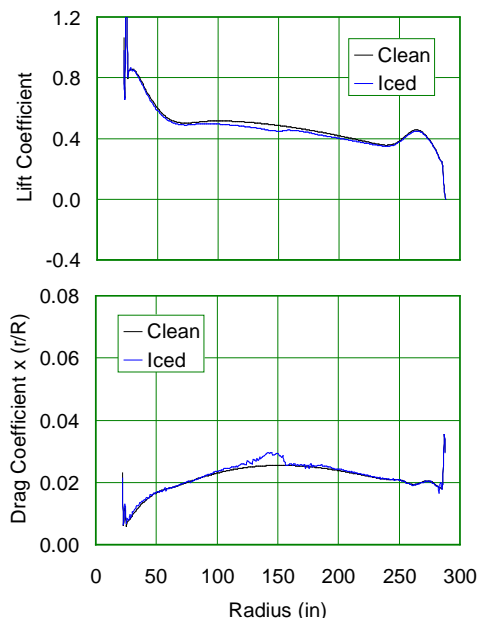


Figure 14.—Blade loads for the clean and iced rotor near the maximum gross weight hover condition.

shows that lift and drag are impacted the most near the 50 percent span location for this icing condition. Intuitively, this is where the largest ice shape is grown. The blade loads outboard of 50 percent seem relatively unaffected by the ice shape which suggests that the hover analysis is not properly capturing the impact of the ice on rotor performance.

Comparisons of Mach contours at station 150 (Figure 15) and 227 (Figure 16) suggest the ice shape over the outboard section is more aligned with the flow and therefore is less detrimental. This stresses the importance of accurately capturing the ice shapes.

Conclusions

A high fidelity ice accretion and rotor performance degradation methodology was presented and applied to a rotorcraft in hover. The process uses computational fluid dynamics to establish clean and iced rotor performance. The ice growth assumes 2D flow along the radius of the blade and is accreted using a loose coupling between 2D CFD and Lewice3D. Application to the UH-1H in hover is the first step in the validation of the process as the problem is simplified because there is no azimuthal variation in flow conditions to consider during the ice analysis. The correlation in predicted ice shape is good however the ensuing rotor performance degradation is under-predicted by 50 percent. Follow-on work will include the application of this methodology to forward flight.

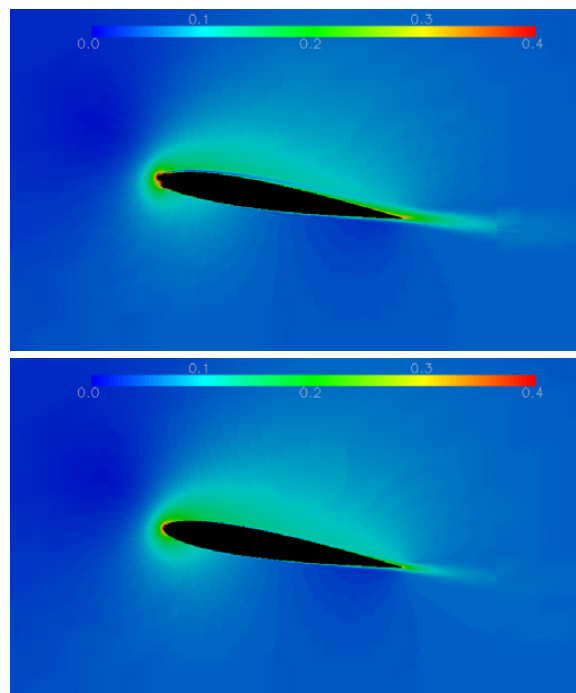


Figure 15.—Mach contours for the clean (bottom) and iced (top) rotor at station 150 near the maximum gross weight hover condition.

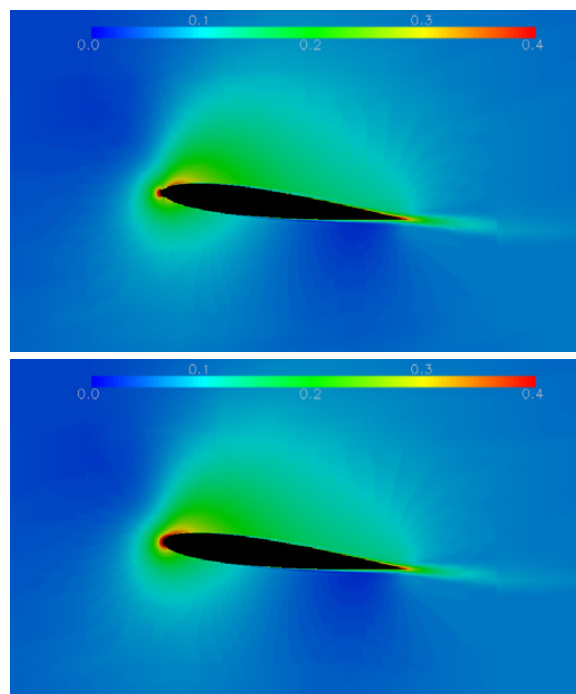


Figure 16.—Mach contours for the clean (bottom) and iced (top) rotor at station 227 near the maximum gross weight hover condition.

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14. ABSTRACT A high fidelity analysis method is proposed to evaluate the ice accumulation and the ensuing rotor performance degradation for a helicopter flying through an icing cloud. The process uses computational fluid dynamics (CFD) coupled to a rotorcraft comprehensive code to establish the aerodynamic environment of a trimmed rotor prior to icing. Based on local aerodynamic conditions along the rotor span and accounting for the azimuthal variation, an ice accumulation analysis using NASA's Lewice3D code is made to establish the ice geometry. Degraded rotor performance is quantified by repeating the high fidelity rotor analysis with updates which account for ice shape and mass. The process is applied on a full-scale UH-1H helicopter in hover using data recorded during the Helicopter Icing Flight Test Program.					
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